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ABSTRACT

This document describes methods for designing and building two types of rockets--rockets from paper and rockets from bottles. Devices used for measuring the heights that the rockets obtain are also discussed. (KHR)

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Air-Powered Rockets

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Air Rocketry

Air rocketry involves the flight of rockets using compressed air as the motive force for the vehicles. This method for propelling rockets is relatively inexpensive when compared to rockets that burn fuel contained in rocket motors. Also, the items used in the construction of these rockets are inexpensive. This translates into lots of science and math activities for little cost. Moreover, these projects are tons of fun.

Two types of rockets are presented in this paper. One is constructed from paper and the other from plastic bottles. Each use tape, metallic washers, and cardboard. Unless these rockets land on hard surfaces (e.g., parking lot), they may be reused several times. A bicycle pump is used to energize the launcher. The latter are easy to manufacture and provide years of service.

The performance of these rockets may be regulated to correspond to a particular grade level. Maximum performance of each extends into hundreds of feet in terms of distance or altitude. Similarly, the velocity of these projectiles may exceed 100 mph.

Paper Rockets

A simple rocket powered by pneumatic or air pressure may be used to demonstrate thrust and Newton's Laws. The rocket launcher presented in this section is a derivative of one used by staff members of the Waco Museum in Troy, Ohio. In addition to demonstrating thrust and Newton's Law, a feature of the launcher depicted herein provides for exercises regarding aeronautical engineering. Because the launcher may be changed to accommodate various diameter rockets and rocket designs may incorporate a variety of different fins, nose cones, and other variables, contests to determine which configuration produces the greatest distance or height for the same launching pressure may be employed to study the effect of rocket design on flight characteristics.

To broaden the range of implementation as far as age groups are concerned, three levels of paper

rocketry have been developed. Low pressure units are suitable for lower elementary grade levels, medium pressure rockets are appropriate for middle school students, and high pressure rockets are ideal for high school students and adult participants. The rocket launcher used for high-pressure paper rockets may be used to launch all units, while a simpler low-pressure launcher manufactured from PVC should be used only to launch low pressure rockets.

Another variable that may limit rocket level is the size of the launch area. When launching high-pressure rockets for maximum distance, ensure that the firing range has around 1,000 feet of linear open space. That's more than three football fields placed end-to-end. In terms of width, the firing range should be around the width of a football field or around 150 feet. Unless the rocket has some unsavory design flaw, it should safely touchdown within the prescribed area. Low pressure rockets may be fired in an area the size of a football field.

A brief set of instructions is provided for the low-pressure rockets and high-pressure models. Illustrations are provided for the production of high pressure rockets. Those building low- and medium-pressure rockets may refer to the high-pressure illustrations as they are applicable to the generation of all rockets. Where needed, the differences between the construction processes are addressed.

Low Pressure Paper Rockets

The low-pressure paper rockets are constructed from sheets of paper usually 8½" by 11". If desired, larger or smaller pieces of paper may be used to vary structural strength and weight at liftoff. Tape is used during the construction process to hold the various pieces together. Refer to the illustrations presented in the section on high-pressure paper rockets for further details.

Launch pressures for low-pressure rockets should not exceed 80 psi. Forty to sixty psi normally provide adequate performance. When necessary, adjust the pressure to accommodate the launching

range. In other words, when firing rockets in a confined area, limit the pressure to keep the rockets within the assigned space. If excessive pressure is used during launch, it is likely that the rocket will be unable to withstand the launch force. Consequently, the rocket will develop a tear or portions of the rocket may be blown into confetti. For this reason, keep everyone behind the launcher during flight operations.

Because tremendous force and velocities are generated during the flights of these rockets, caution should be exercised to prevent personal injury and damage to property. Medium-pressure rockets have been timed at 100-plus miles per hour with the maximum speed registering 170 mph! Speed trials of high-pressure paper rockets are pending. NEVER AIM THESE ROCKETS IN A DIRECTION THAT MAY POSSIBLY CAUSE INJURY OR DAMAGE as once the pressure is released there is no possible way to stop the flights of these projectiles. These paper rockets fly as a result of the force released during liftoff. They do not continue to produce thrust during the course of the flight. As such, they are merely projectiles instead of true rockets. BB gun ammunition, pellets, bullets, slingshot projectiles, artillery shells, etc. all fly in a similar fashion.

The low-pressure rocket launcher is fashioned from PVC pipe and fittings, a pressure gauge, a valve that quickly opens, an inflation stem and associated hardware, and a wooden base. Screws, threaded rods, T-nuts, and wing nuts are used for affixing the launcher to the wooden base. Tools for cutting PVC, a drill, C" NPT (pipe thread) tap, saw, fly or hole cutter, and wrenches are needed during the construction process. Teflon tape, PVC cleaner, and PVC cement are used to manufacture the pressure chamber and launcher. For more details concerning the fabrication of this unit, contact the author as listed on the cover page of this companion guide. As an alternative, refer to the high-pressure rocket launcher presented in this unit for construction details. The high-pressure model may be used for launching all three levels of paper rockets.

Low-pressure rockets are fashioned from ordinary paper and tape. The first step is to select the

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diameter of the fuselage. Available diameters include ¾" and ½" PVC and ½" CPVC. Three variables have to be considered during the selection process. The first is force. If a constant liftoff pressure (e.g., 80 psi) is used for each size, then the amount of force varies with the diameter of the rocket. Because force equals area times pressure (F = A X P), the amount of force for each size varies significantly with the larger sizes having more force during liftoff.

Along with size comes drag. The larger the diameter, the greater the drag. In general, the atmosphere imposes greater opposition to the movement of larger diameter rockets than it does smaller rockets when all other conditions are equal. Drag must be overcome, therefore is the advantage of force gained by diameter consumed by drag when launching larger diameter units instead of smaller ones?

Another issue that must be considered is structural integrity. As the diameter of the rocket increases, does the relative strength of the structure diminish? In other words, does the increase in force during liftoff in combination with the strength of the fuselage increase the likelihood of structural failure of the rocket? Astronautical engineers have to deal with such issues when they design spacecraft. They too have to consider issues such as thrust, size, structure, etc. necessary for the mission of the vehicle. And, as demonstrated in this exercise, astronautical engineers have to make compromises between thrust, size, structure, and so forth.

After selecting the desired size of the fuselage, form the structure by wrapping a sheet of paper around a segment PVC pipe used as a mold. With a little experience, the appropriate tightness of fit around the mold may be determined. If too tight, the unit may not depart the launch pad in one piece. In such instances, the nose cone may separate from the fuselage. If too loose, valuable liftoff pressure will escape between the inside diameter of the rocket and the launcher. One way to achieve a workable fit is to use a technique developed by the members of the Waco Museum. They affix a strip of tape to the outer diameter of the mold tube. This measure provides a slight clearance between the inner diameter of the

fuselage and the outer diameter of the launch tube. After wrapping the paper around the mold, tape the edge of the fuselage assembly to keep the paper from unwrapping itself. It might be advantageous to seal the end of the fuselage before attaching the nose cone. Either apply tape across the end of the fuselage or following the approach taken by the Waco Museum staff. They crimp the end of the fuselage and tape over the crimp. The nose cone may be fashioned from a circular piece of paper that has a pie-shaped wedge removed from the material. Form a cone and attach the unit to the end of the fuselage with tape. Fins should be constructed and added to the other end of the rocket. It may be advantageous to form the fins from stiffer material (e.g., note cards). The size, design, and number of fins are options that should be considered. If desired, add a little spin to the rocket by including a slight angle on the fins when attaching them to the fuselage. By spinning the rocket during flight, stability is enhanced. On the downside, spinning high-pressure rockets tends to diminish performance as the spinning action generates additional drag. Spinning of full-sized space vehicles is used by NASA and other space agencies for stability. Note how satellites deployed from the shuttle rotate as they exit the cargo bay. This technique is also used when passing a football, discharging a firearm, or shooting an arrow. For additional information on stability generated by spinning objects, refer to the section of Gyroscopic Rigidity presented in a subsequent portion of this booklet.

Medium- and High-Pressure Paper Rockets

For more advanced builders, the paper rocket activity may be modified to increase performance. Both medium- and high-pressure paper rockets have incredible performance. Because of the use of ballast under the nose cone and the astonishing velocities generated during launch (well in excess of 100 mph), these rockets greatly increase the risk of injury to personnel and damage to property. They are not suitable for unsupervised use and should only be flown in open spaces and in situations where adult

directors of the project are in complete control of the participants.

As with the low-pressure models, the first decision that has to be made involves the diameter of the rocket. Three diameters seem to work well: ½" and ¾" PVC and ½" CPVC size pipe. Such material may be procured from a hardware store. The segment of pipes used as molds for the rocket tube should be slightly longer than dimension of the paper (e.g., 12"). Refer to the illustration revealing the different launch tubes.

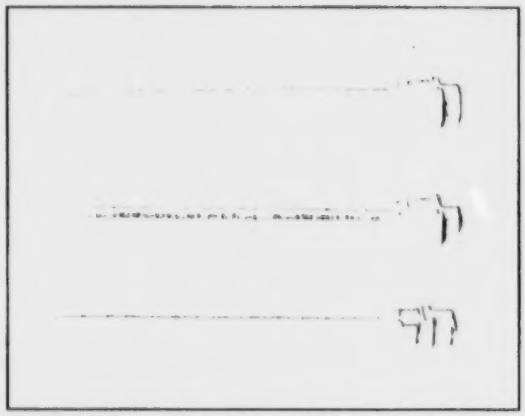

Figure 1: Different Sizes of Launch Tubes. The Top Tube is ¾" PVC, the Middle Tube is ½" PVC, and the Bottom Tube is ½" CPVC.

The threaded adapters at the ends of the launch tubes screw into the end of the launcher. This provides a quick means of changing from one size rocket to another.

Materials and tools needed to produce a low-, medium-, or high-pressure paper rocket are presented in the next illustration. When constructing low-pressure rockets, conventional sheets of paper may be used. Also, there is no need for reinforcement via duct tape and nylon corded shipping tape. Medium-pressure rockets may be launched with pressures as high as 150 psi. The velocities, distances, and altitudes generated by such rockets are impressive. From the items presented, the use of nylon-corded shipping tape may be omitted. The use of card-stock rather than ordinary paper is recommended. If card-stock is not available, use paper with a 24-pound rating (e.g.,

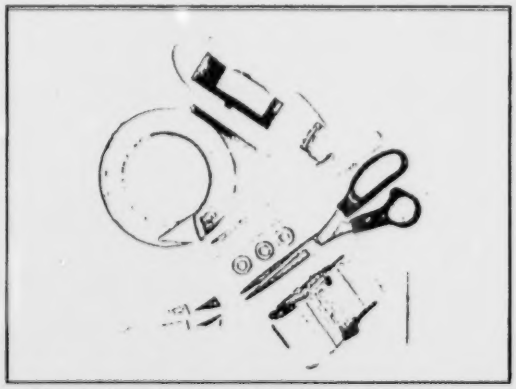

Figure 2: Items Needed to Manufacture Paper Rockets.

bond). All of the items shown on the illustration are needed to manufacture high-pressure rockets.

The first step in the construction of a paper rocket is to build the rocket tube or the body of the rocket. This is accomplished by rolling the paper (low-pressure models) or cardstock (medium- and high-pressure rockets) around the desired diameter mold. Apply cellophane tape to the entire length of the edge of the paper to secure the shape of the rocket body. As previously indicated under the section detailing the construction of low-pressure rockets, the builder has the liberty to roll the material as tightly or as loosely as desired. Tubes that are too tight may suffer structural failure during launch and those that are too loose may experience a reduction in performance. With experience, builders may develop a "feel" for how tight to roll the rocket body.

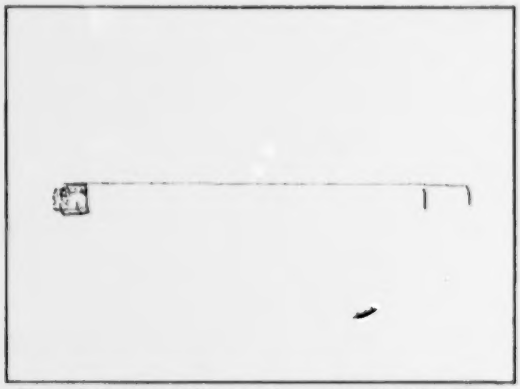

Figure 3: Cardstock Wrapped Around the Mold (½" PVC Pipe). In this Illustration, the Left End has been Crimped and Sealed and Ballast has been added. Note a Portion of the PVC Pipe Protruding from the Right End of the Rocket Tube.

Following the formation of the rocket tube, slide the tube so that one inch of the tube protrudes beyong the PVC mold. Crimp the end by pressing segments of the tube towards the center. Carefully tape the end of the tube so that an air-tight closure results.

Next, when building medium- and high-pressure rockets, apply ballast to the sealed end of the rocket tube. Common hardware store washers may be used for this purpose. Be certain to select washers that closely match the diameter of the rocket tube. Modeling clay, coins, and other material may be substituted for washers. Regardless of the material used for ballast, carefully align the ballast so that it is centered with the longitudinal axis of the rocket tube. In this example, three washers are used for the purpose of ballast. Three washers may not be the most appropriate amount of ballast for this rocket, but

should provide enough mass to ensure a respectable flight. Secure the ballast using tape of some suitable means. Refer to the illustration showing the installation of ballast.

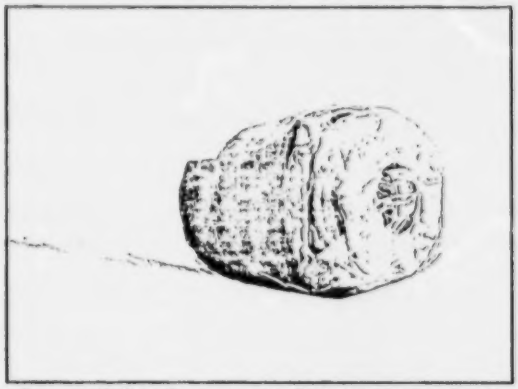

Figure 4: Ballast Secured to the Sealed End of the Rocket Tube

The quantity of ballast has an enormous influence on the performance of the rocket. If too much ballast is incorporated into the construction of the rocket, the vehicle will be too heavy and will not travel very far. If too little ballast is used, the rocket will not have enough mass to perform well. Consider the following. Imagine that you are going to throw three balls. One is a wiffle ball (a hollow plastic ball the size of a baseball), the second ball is a baseball, and the third ball is a cannonball (a heavy steel ball). In this example, you are to throw each ball as far as you can using the same level of exertion. Which ball will travel the greatest distance? Obviously, the baseball will emerge the winner as the wiffle ball is too light and the cannonball is too heavy.

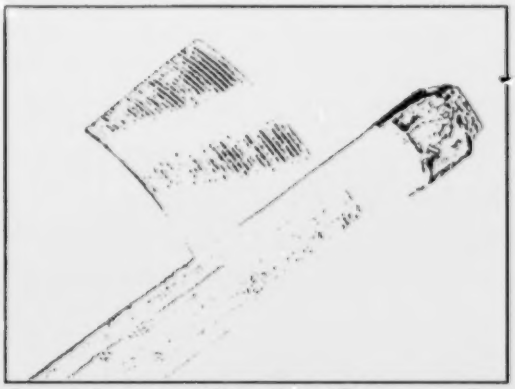

Figure 5: Application of Nylon-Corded Reinforcement Tape for High-Pressure Rockets

After sealing the end of the paper tube and affixing the ballast, builders of high-pressure models should reinforce the rocket tube. This measure is necessary as the force absorbed by the rocket during a high-pressure takeoff will likely cause the paper tube to either unroll or experience a structural failure. A reinforcement material that works well is the nylon-corded shipping tape. Non-reinforced shipping tape or duct tape is likely to fail when used for this purpose. Apply the shipping

tape so that nylon cord runs laterally across the rocket body. This arrangement places the nylon cord in a tensile load. If the tape is applied so that the nylon cord runs the length of the rocket tube, the mylar between the nylon cords will fail. Cut a series of strips long enough to wrap around the rocket tube. Locate the ends of the tape strips so that they are not close to the edge of the cardstock that is secured by the cellophane tape. Starting from the bottom of the rocket, wrap the tape around the body of the rocket tube. Continue to apply each successive strip until the entire length of the rocket tube has been reinforced. Refer to the corresponding illustration for addition information.

After reinforcing the rocket body, apply pieces of duct tape to the exterior of the rocket tube. This step should also be taken for medium-pressure rockets. The application of duct tape at this junction is to provide a more aerodynamic surface to the rocket tube for the high-pressure models and to add strength to the rocket tubes of medium-pressure rockets. Because of the high speeds experienced by the rockets during flight, carefully apply the tape to minimize wrinkles and other flaws that will tend to create drag. Refer to the associated figure for addition information.

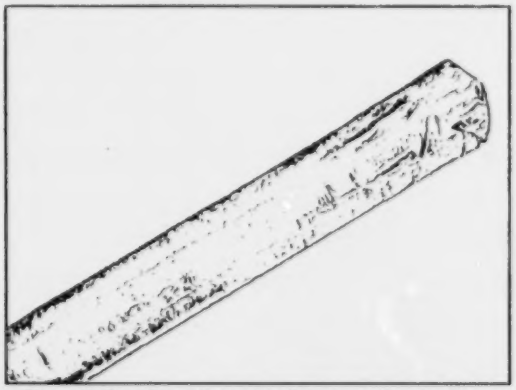

Figure 6: Duct Tape Applied to Exterior of Rocket Tube. This Measure is Only Needed for Medium- and High-Pressure Rockets.

The nose cone may now be attached. The nose cone shown in this illustration was manufactured from a piece of card stock cut into a circle. A cut from the edge of the circle was made to the center of same. Then a cone was formed by manipulating the edges of the cut. When the outside diameter of the opened-end of the cone matches the outside diameter of the rocket body, tape the edges of the nose cone material to retain this shape. Cellophane tape works well for this operation. After forming the cone,

carefully align it on the end of the rocket tube that contains the ballast. Be certain to position the cone on the rocket as straight as possible to minimize aerodynamic drag during flight. Attach the nose cone to the rocket body using tape. See the illustration of the nose cone installation.

Figure 7: Nose Cone Installation

The final step in the construction of the rocket is the attachment of the fins. Without fins, the rocket will fly in an unstable manner. Consequently, as it wobbles along its trajectory, an inordinate amount of drag is generated. The end result is loss of performance. The size and number of fins are variables that affect the performance of the rocket. If the fins are quite large, a stable flight generally occurs. But, large fins generate more drag than small fins for other conditions being the same. If the fins are too small, the rocket may lack stability. The optimum size of the fins is also associated with the velocity of the craft. Slower moving rockets generally require larger fins than those that fly at high speeds. Because the rocket shown in this demonstration will likely exceed 100 mph, the designer opted to use four small fins. The fins were cut from a thin cardboard box and attached using cellophane tape. See the figure regarding fin installation for additional details.

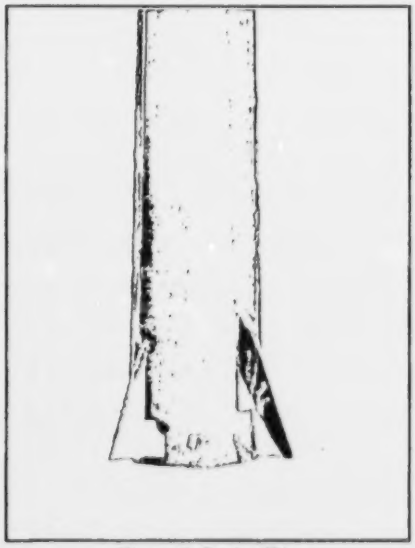

Figure 8: Rocket Fins

Another issue that must be observed during this phase of the construction process is fin alignment. If the fins are misaligned or are unevenly spaced or are located in an

ineffective location, the rocket will lack stability. The net result will be a reduction in the performance of the projectile.

Launching Paper Rockets

Special launchers are needed to fly the paper rockets. One model is only suitable to fly the low-pressure rockets. The high-pressure launcher may be used with all categories of paper rockets.

The source of power for propelling the rockets is compressed air. Where any source of compressed may be used, a bicycle pump works well. However, for medium- and high-pressure launches, a suitable bicycle pump is required. Standard units purchased at department stores may only generate around 80 psi of pressure. To purchase a high-pressure pump, contact a bicycle store. One brand and model of pump that works well is the Zéfal HP Husky. This pump has a steel cylinder with a cast base. It may be rebuilt by installing new parts associated with the piston. The pump also includes a pressure gauge.

Construction characteristics of a quality high-pressure pump include a cylinder that has a rather small diameter. If the pump has a large diameter cylinder, the pressure will quickly build to around 80 psi and then it will take a great deal of exertion to attain a launch pressure of 250 psi or more. If you are planning to use an air compressor, be aware that many have features that will prevent the pump from reaching pressure greater than 125 psi. In any event, a little research is needed to acquire the proper gear in terms of compressing air. On a side note, if students are involved in operating the bicycle pump, they will soon learn a lesson about how much power

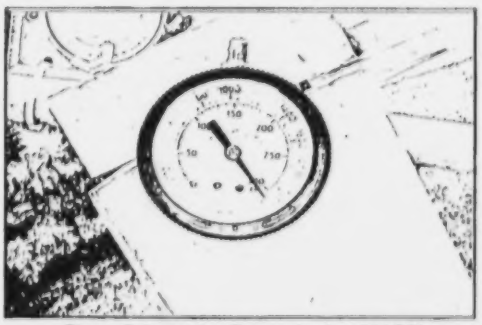

Figure 9: Launcher Pressurized to 300 PSI

is needed to compress air to high levels. Too often, people take air for granted and are unaware of its properties.

As previously mentioned, select a suitable site for flying the paper rockets. Something around the size of a standard football field is adequate for flying the best performing low-pressure rockets. The medium- and high-pressure models need a site that is roughly the length of three football fields placed end-to-end and about the same width as a football field. If the rockets are to be launched straight up, or vertically, be aware that the medium- and high-pressure rockets accelerate to the point that those standing beneath the launcher may lose sight of the rockets as they ascend. When this occurs, those standing near the launcher will have no idea where the rockets will land and can only hope that they are not struck by the descending rockets. The descent rate is quite high and the rockets typically "yard dart" into the ground. It is a good idea to wear protective headgear when performing vertical launches. On the same note, those in vicinity of the launch area must also keep a close vigilant on the flight path of the rocket.

To prepare the launcher for a flight, first select the proper launch tube. The three choices are the ½" CPVC, the ½" PVC, or the ¾" PVC. On the low-pressure launcher, the launch tubes are held in place by friction. Merely push the desired rod in place and give it about ¼ of turn as you push it into the launch head. The medium- and high-pressure launch tubes must be screwed into the launch head. Place the rocket on the launch tube before pressurizing the launcher. This minimizes the risk of injury in that the rocket may not be inadvertently launched. Clear the area in front of the launcher before proceeding to the next steps. Close the valve and attach the pneumatic line. Pressurize the launcher to the desired psi. Again, ensure that no one is standing in front of or adjacent to the rocket during launch. Bear in mind that poorly constructed rockets may burst apart during liftoff. Therefore, to minimize risk to personnel, everyone should be behind the rocket during this procedure.

Before sending the rocket skyward, set the desired launch angle. When shooting for distance, try settings that range from 20 to 45 . If the objective is to shoot for altitude, lift the launcher until the rocket is vertical or 90 . The angle of the launcher may also be adjusted to compensate for strong winds. In the corresponding figure, the rocket launcher is set for a 30 trajectory.

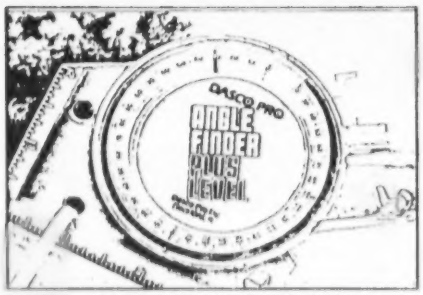

Figure 10: Launcher Set for 30 Trajectory

Once the rocket is mounted on the launch tube, the trajectory angle set, and the launcher pressurized, the rocket is ready for flight. Initiate the countdown and open the valve at "ZERO" or "LIFTOFF." For best performance, rapidly open the valve. Opening the valve in a slow fashion will greatly reduce performance.

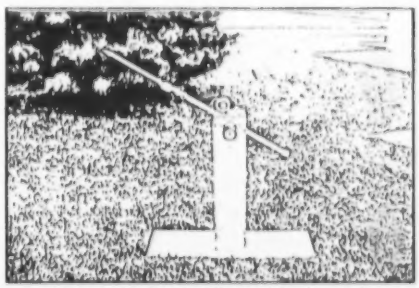
Figure 11: Rocket Poised for Launch

If trackers are used to time the flight of the rocket or measure angles with clinometers, be certain that they are alerted to the launch operation. Normally, the countdown arouses everyone's attention. For measuring linear distance, a measuring wheel works well. It is often better to first find the rocket at its touchdown site and measure the distance to the launch pad in a straight line. If the rocket is not terribly mangled after the flight, it may be flown again. However, the paper rockets are not very durable and may only have a single good launch.

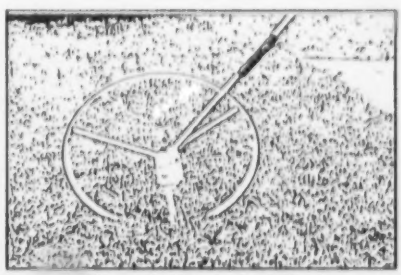
Figure 12: Measuring Wheel

Newton's Law Associated with the Paper Rockets

In terms of laws of motion, Newton's First Law states that a body at rest remains at rest, or a body in motion continues its motion in a straight line until acted on by an external force. When the rocket is poised for liftoff on the launcher, it is in a state of rest. It remains so until the pneumatic charge acts upon it or some other force disturbs it. When the rocket is in flight, it basically travels in a straight line. However, gravity, drag, wind, and other aerodynamic and gyroscopic forces act on the rocket during the entire duration of its flight.

Newton's Second Law is directed at acceleration: the acceleration of a given body is proportional to the force acting on it. When the pneumatic charge is released, the force of the blast acts on the projectile, causing it to accelerate. For all other conditions equal, the greater the force, the greater the acceleration. However, other conditions do not remain the same. The quantity of drag changes with the size of the rocket and its velocity. In addition, the relationship between velocity and drag is not linear. As velocity increases, drag increases at an exponential rate.

Newton's Third Law, for every action there is an equal and opposite reaction, is demonstrated during liftoff. As the air pressure is release, the mass of pressurized air contained in the launcher rapidly escapes the chamber where it was housed. Because the rocket is placed in the path of the rushing mass of air, it is given a propelling moment that results in flight. The reaction to this rapid discharge of air is absorbed by the launcher. Because the launcher is relatively heavy and resting on a solid surface (e.g., the ground), the reactive force applied during liftoff is insufficient to overcome the weight and fiction presented by the launcher. If it were mounted so that it was weightless and frictionless, the launcher would have a visible reaction to the release of the air charge. It would travel in a direction opposite that of the rocket. A similar reaction is obtained when firing a rifle, it "kicks" in a direction opposite that of the bullet.

Math exercises to determine the height, force, work, power, horsepower, and average velocity of the rocket may be conducted. To measure the height of a rocket launched in a vertical trajectory, form a

right triangle between the tracking station or viewing area, the launch pad, and the apogee of the rocket. The apogee of the rocket occurs when it reaches its maximum altitude. In reality, there may be some error in this method as the rocket may not travel in a perfect vertical path above the launching pad. Any error, however, does not detract from the mathematical and science benefits provided by this exercise. When only one tracker is used to measure the height of the rocket, select a location slightly downwind of the launch area. For best results, situate the spotter so that the wind is blowing directly on the person's left or right shoulder, as appropriate. To minimize error for the purpose of this manual, the measurements taken by the author and his associates were conducted in still air. The flight that provided the data for the ensuing examples was nearly straight up and down as the rocket landed within a few feet of the launching mechanism.

An instrument, known as a clinometer, was used to measure the angle formed by the rocket as it reached its apogee. To construct an inexpensive clinometer, insert a segment of string through the hole in the center of the ruler portion of a common, six-inch protractor. Tie a knot in one end of the string. Attach a washer or suitable weight to the other end of the string. Thread the ends of a rubber band through both holes of the protractor so that a small loop protrudes from the holes. Once the rubber band is in place, slip a milkshake size straw through each loop of the rubber band. Refer to the illustration revealing the ***"Simple Clinometer"*** for construction details.

To measure the height of a rocket, track its flight through the straw. At the apogee (highest point) of the flight of the rocket, press the string of the weight against the protractor to freeze the reading. Read the appropriate angle scale to measure the elevation above the horizon.

The angle formed from the tracking station to the rocket's apogee may be used in conjunction with the linear distance between the launch pad and the tracking station to determine the height of the rocket. Based on the trigonometry of a triangle with a right angle, the Tangent of = the length of the opposite leg

divided by the length of the adjacent leg. The flight of the rocket is represented by the length of the opposite leg. Using algebra to solve for the opposite leg, our formula for the height of the rocket becomes: Alt = Tan X the length of the Adjacent leg. Using an adjacent leg of 100 feet simplifies the calculation. Of course, the accuracy of this technique is compromised when the rocket does not ascend in a perfect vertical trajectory. To correct for this error, predict which way the rocket will veer during its ascent and station the person performing the tracking at that position. The initial tracking site may be found by standing at the launch pad and facing into the wind. Measure the adjacent leg perpendicular to the wind. Once this is accomplished, move downwind the anticipated amount of drift to be experienced by the rocket as it approaches apogee. After a couple of flights, adjustments to the tracking site may be made.

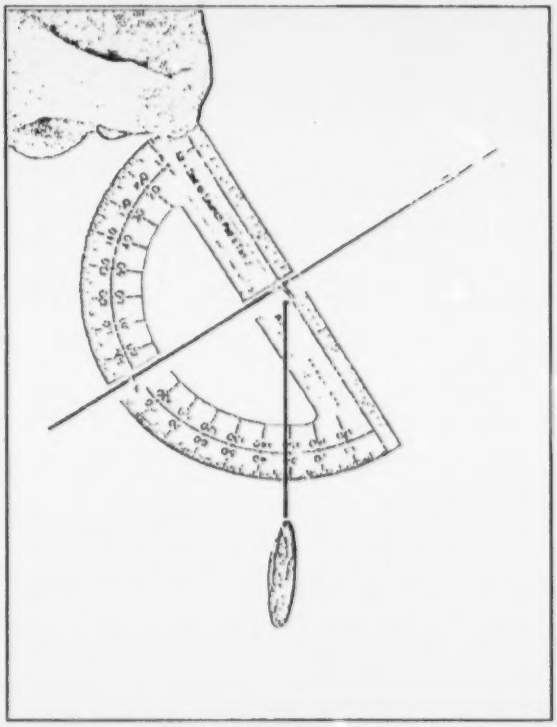

Figure 13: Simple Clinometer

Data generated during the vertical launch of a low-pressure rocket registered an angle of 44 at the apogee of the flight. The launch pressure was 40 psi. A clinometer stationed 100' away (30.48 meters) was used to measure the angle. To calculate the height, multiply the distance of the tracking station from the launch pad by the tangent of the angle and add the height of the tracker's eye. Because the rocket may be some distance above the ground due to the height of the launching mechanism, this distance should be subtracted to determine the altitude attained by the dynamic action of the force acting

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on the rocket.

Handheld calculators greatly simplify the calculation process. If a calculator is to be used, check specific instructions for determining the value of tangents. Many calculators that contain trigonometric functions complete the calculations using the following steps. Enter the degree reading provided by the clinometer. After entering the value, depress the tangent (TAN) key. Make certain that the calculator is in the degree-mode and not some other denomination (e.g., radians). Next, multiply this value by the linear distance from the launch pad to the clinometer. Press the equal sign (=). The display of the calculator reveals the height of the rocket above the viewing plane. To determine the height above the surface, add the height of the tracker's eye above the ground to the value emerging from the calculator.

If a trigonometric calculator is unavailable, refer to a "Trig Table" in a math book for the corresponding values. Having a distance of 100' between the launching pad and the tracking location simplifies the arithmetic when Trig Tables are used because shifting the decimal two columns to the right yields the altitude above the viewing plane. The height of the eye of the tracker should be added to more correctly determine the height attained by the rocket.

In a sample flight of a low-pressure rocket, an angle of 44 was read from the tracking station situated 100' from the launching pad. Using the aforementioned procedure, the altitude attained by the rocket was 99.57 feet (30.35 meters). The tangent of 44 equals .9657. This value times 100 feet equals 96.57 feet (29.43 meters). An additional 3 feet (0.91 meters) were added to compensate for the height of the tracker and the elevation of the launching mechanism. The eye of the tracker was 5½ feet above the ground and the rocket was 2½ feet from the surface when poised for liftoff.

The formula for determining force is: Force = Area X Pressure. The area of the inside diameter of the rocket may be calculated by squaring the radius and multiplying by . To figure the radius, measure the diameter of the inside of the rocket, or the outside of the launch rod, and divide by 2. The ½" PVC pipe

used for this experiment measured 0.838". Using r^2 to calculate the area, first divide the diameter by 2. This yields a radius of 0.419". After squaring the radius (which becomes 0.176), multiply by (3.142). The area of the circle representing the cross-section of the rocket is 0.55 square-inches. Using a launch pressure of 40 pounds per square inch (psi), the force applied to the rocket the moment the valve was opened equaled 40 psi X 0.55 square inches. After all the calculations and cancellation of units are performed, the rocket had a little more than 22 pounds of force applied to it at the time of liftoff. When it is taken into consideration that the vehicle weighed only 6.1 grams or 0.215 ounces, it is easy to understand why the rocket traveled so high.

To calculate the work performed during the previous flight, the weight of the rocket should be taken into consideration. Not including compensation for drag and other forces offering resistance to the flight of the rocket, the weight of the rocket times the height attained during its flight equals the amount of work. In other words, if the rocket was manually lifted to its apogee, a certain amount of work would be performed. The calculations provided are conservative as the aforementioned resistance, known as drag, is not included. The rocket tested by the author and his associates weighed 6.1 grams or 0.013 pounds. Data collected from one of the test flights indicated that the altitude attained was 99.57 feet. Nearly all of the flights conducted during a series of tests reached similar altitudes. The work necessary to lift this rocket 99.57 feet is 1.294 foot-pounds (Work = Weight X Distance).

Because the time it took to reach the apogee was measured, power may be calculated. Once again, these calculations are conservative as drag is not included. In this example, the rocket reached its apogee in 2.2 seconds. Power equals work divided by time (Power = Work ÷ Time). In this example, 1.294 foot-pounds ÷ 2.2 seconds equals 0.583 foot-pounds per second. To convert this value into horsepower, divide power by 550 (33,000 should be used if power is in minutes rather than seconds). The horsepower employed during the flight of this air rocket equaled 0.001 horsepower (HP = 0.585 ÷ 550 =

0.001). Although the horsepower seems low, remember that it was applied to pieces of paper formed into a rocket using tape. Also, the power needed to overcome drag was not considered.

The average velocity during ascent and descent may be calculated if the time for each and the distance traveled (in this case altitude) is known. The timing process was performed with a common sports watch that included a lap counter. With this feature, the time to apogee was taken by depressing the Start/Stop button at liftoff and pressing the Lap Counter button when the rocket reached apogee. The entire time of the flight was measured by depressing the Start/Stop button when the rocket landed. The difference between the apogee time and the total time equaled how long it took the rocket to descend. The rocket reached its apogee of 99.57 feet (30.34 meters) in 2.2 seconds. The average velocity equals the distance traveled divided by the total time needed to traverse the distance (Average Velocity = Distance ÷ Time). In this example: 99.57 feet ÷ 2.2 seconds equals 45.26 feet per second (13.79 meters per second). Using the conversion multiplier of 0.6818, 45.26 feet per second equals 30.86 miles per hour (49.66 kilometers per hour). The descent was somewhat slower. It took 2.89 seconds for the rocket to alight from its apogee. Therefore, the average descent speed was 99.57 feet ÷ 2.89 seconds or 34.45 feet per second (10.50 meters per second). This translates into 23.48 miles per hour or 37.80 kilometers per hour. The multiplier for converting feet per second into kilometers per hour is 1.0973. The fact that these are average velocities must be considered. When the rocket lifted off, it had a tremendous quantity of acceleration. It then decelerated until its apogee. During descent, the rocket accelerated as it descended. It is unlikely that its terminal velocity (the maximum possible speed attainable during its descent) was reached.

The air rocket is a wonderful way to demonstrate Newton's Laws of Motion and solve math problems. It is an inexpensive device to construct and operate. The units used by the author have hundreds of launches. The materials used for constructing the rockets are readily available and practically

cost-free. This allows for unlimited experimentation as the number of designs is limited only by one's imagination. A properly constructed launcher is capable of propelling rockets more than 130 feet with as little as 40 psi of pressure. An ordinary bicycle pump may be used to pressurize the chamber. This demonstrator may be used inside large rooms (e.g., gymnasiums) as long as the pressure used for liftoff is appropriate for the circumstances. High-pressure units are routinely attaining flights of 600 feet with well-designed rockets approaching 800 feet of travel. **BEWARE: SEVERE INJURIES AND DAMAGE TO PROPERTY MAY RESULT FROM RECKLESS USE.**

Two-Liter Water Bottle Rocket

A most marvelous illustration on Newton's Laws of Motion may be demonstrated using two-liter plastic bottles, duct tape, some washers, cardboard, and a launch pad. The techniques and information used to describe this activity have been employed by numerous individuals, but perhaps the best approach is provided by Dr. Robert Horton of Ohio State University. He has developed a program known as, ***Rockets Away***. His program contains various forms of instructions, including a computer program for designing and test flying the rockets. There are a couple of companion books and an available launching pad. To find out more about ***Rockets Away***, log into the following web site: "http://www.ag.ohio-state.edu/~rockets/". (Do not include the quotation marks.) The vendor for the launcher is Versey Enterprises. They may be contacted via e-mail at versey@juno.com or by phone by dialing (208) 357-3428.

Information concerning Newton's Laws of Motion and measuring techniques were provided in the previous section on "Paper Rockets." To save paper and space, that data are not duplicated in this section. To maximize the benefits of this lesson, keep track of design elements (e.g., number of washers, volume of water, number and size of fins, etc.) and compare results of flights to determine superior design features. Another activity that may be undertaken is to experiment using the same rocket and varying a

single element, such as the level of water, to discover the best launch configuration for a particular design. Graph the results to help visualize the performance of a rocket.

To build a rocket similar to the one illustrated, the following materials and tools are needed: 2 two-liter soft drink bottles made of plastic (DO NOT USE GLASS BOTTLES), a partial roll of duct tape, stiff cardboard for the fins, some hairpins to brace the fins, large diameter steel washers, a razor knife or suitable substitute to cut the plastic bottle and cardboard, water, source of compressed air (bicycle pump), and launch pad.

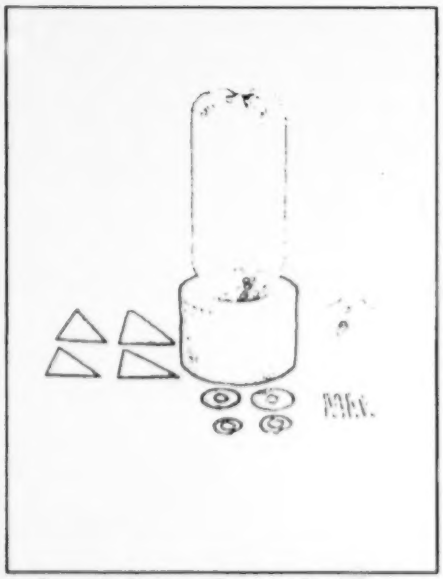

Figure 14: Parts of a Two-Liter Bottle Rocket

Begin by determining the number of washer to use to increase the launch weight of the rocket. It may be necessary to experiment to find the optimum numbers of washers to use as too few and the rocket may not have enough momentum during the coast segment of the flight to reach it highest potential apogee and too many washers will make the vehicle too heavy to reach its optimum apogee. To begin, arrange one of the two-liter plastic bottles so that the filler neck is downward. The bottom of the bottle should be pointing up. Be certain to use a bottle that is in good shape because it will be subjected to high pressure. **Do not use bottles that have**

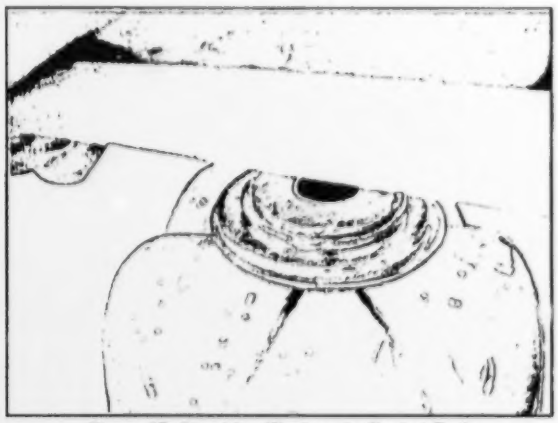

Figure 15: Attaching Washers to Rocket Body

kinks or other deformities that may rupture when pressurized. Secure the desired number of washers to the top of the rocket body using duct tape (former bottom of the bottle). Center the washers on the rocket body to minimize any imbalance. Apply two pieces of tape in the shape of the letter "X" to keep the washers from shifting around.

The material for the nose cone is taken from the remaining two-liter bottle. Using a sharp knife or suitable cutting device, cut the neck away. The next cut should be made where the curved portion of the bottle meets the widest diameter of the bottle. The nose cone is basically a semicircular piece of plastic. Place the nose cone over the top of the rocket body to cover the washers. Carefully center the nose cone to help the rocket fly straight. Tape the nose cone to the rocket body by applying tape around the circumference. Smooth the wrinkles out of the tape. Seal the hole on the top of the nose cone using duct tape. Covering the hole in the nose cone is a measure to reduce drag, or air resistance, experienced by the rocket during flight. Two pieces of tape forming the letter "X" should cover the hole.

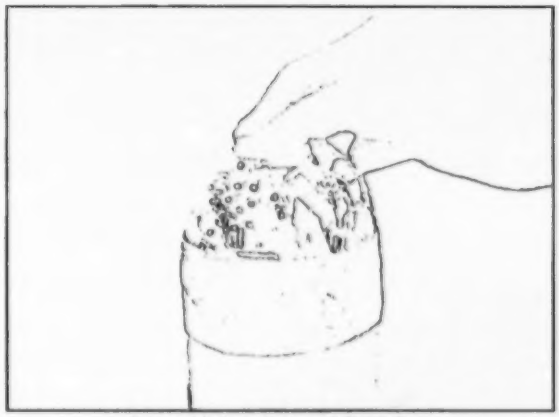

Figure 16: Installation of Nose Cone

Figure 17: Nose Cone Installation

Fins are used to provide a measure of stability to the flight of the rocket. A minimum if two fins should be used, but don't hesitate to apply three or four fins to the rocket body. One decision at this point is to contemplate not only the number of fins, but their size and shape. In this example, four triangular fins were selected. Another decision involves the placement of the fins.

Should they be placed near the top of the rocket or near the bottom by the filler neck?

To stiffen the fins insert the curved end of a hairpin into the edge of each fin. Leave about 3/4" of the legs of the hairpins protruding from the fin. Bend one leg so that it is perpendicular with one side of the fin and bend the remaining leg in the opposite direction. If large fins are used, insert a hairpin near the top and bottom of each fin. Attach each fin using duct tape. Apply the duct tape so that it runs from each side of the fin, over the protruding hairpin legs, and onto to bottle. Ensure that the fins are straight and firmly attached. Accurately arrange the fins so that they are symmetrically affixed to the rocket.

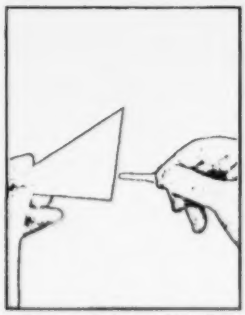

Figure 18: Insert Hair Pin

The final option that must be resolved is how much water to use for liftoff. A good starting point is to fill the bottle with around 30 fluid ounces (887 ml) of water. On subsequent flights, either add or subtract water until the optimum level is determined.

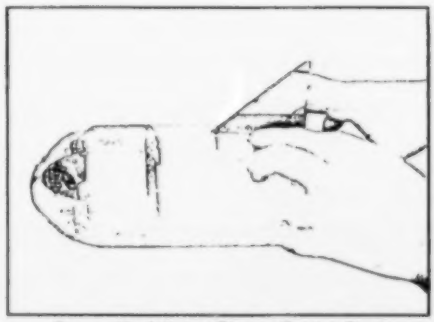

Figure 19: Affixing Fins to Rocket Body

Place the two-liter bottle rocket on the launch pad and insert the launch pin. Pressurize the rocket using a suitable source of compressed air. A bicycle pump works well for this purpose. Often the flight area is confined and care must be taken to minimize the risk of bodily harm or damage to property. Instruct those involved in the activity to remain clear of the rockets during the ascent and descent. Attempting to catch the rockets during their descents will likely result in severe injuries.

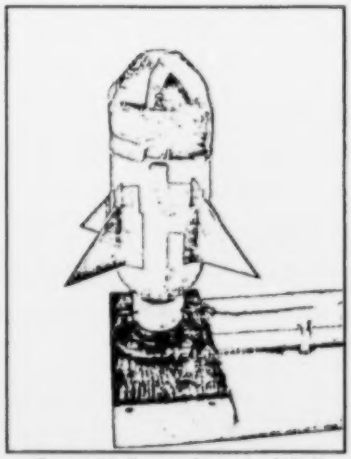

Figure 20: Rocket Poise for Liftoff

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Test the rocket using a moderate pressure (e.g., 60 to 80 psi) as its flight characteristics may result in an unsavory flight. If the flight is true and straight, try a second launch using a higher pressure. Avoid using pressures that may rupture the rocket. The author normally limits the launch pressure from 140 to 150 psi. The launch pressure may further be limited by stiff winds. Because the wind has an affect on the trajectory of the rocket, it may land some distance from the launch site. Consequently, it may land on the top of bystanders, buildings, cars, trees, etc. In such cases, it may be necessary to tilt the launcher so that the rocket is launched slightly into the wind.

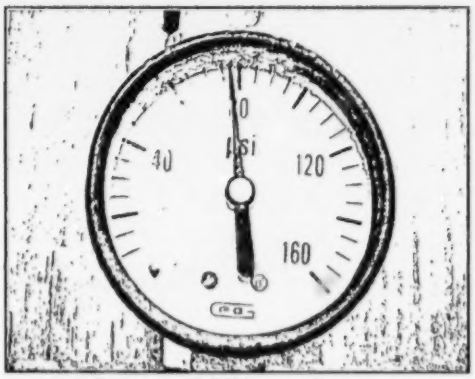

Figure 21: 77 PSI Launch Pressure

Apply the measuring techniques using a clinometer listed in previous section on ***Air Rockets*** to determine the performance of the rockets. Record the results of the flight and evaluate the design of the rocket. If the rocket wobbles during its ascent, implement corrective measures to enhance performance.

The launching mechanism used by the author has a tilting feature. Rockets may be flown from a near horizontal angle to vertical. An exciting activity is to fly the bottle rockets for distance. Surprisingly, these rockets rival the performance of the paper rockets flown under the similar conditions. Unlike the paper rockets, the bottle rockets are easy to track during the course of their trajectory.

This activity leads to numerous discussions. It's a virtual physics bonanza that generates a great deal of excitement and enthusiasm. The cost of this activity is minimal and the longevity of the launching device is such that it may be used for years. The mechanism seen in these illustrations has been used for several years and has well over 1,000 launches. Those desiring to incorporate this exercise in their classroom should construct several different rockets and practice the launching. This rehearsal will come

in handy when helping students construct and fly their rockets. Experiment with one-liter and 20-ounce bottles. Compare their flights to those of two-liter bottles. This is one experiment where the sky is the limit.

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